PB-221 018

SIMULATION OF CHLORIDE CONCENTRATIONS IN THE POTOMAC ESTUARY

Leo J. Hetling

Federal Water Pollution Control Administration
Charlottesville, Virginia

March 1968

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

133

PB 221 018

SIMULATION OF CHLORIDE CONCENTRATIONS IN THE POTOMAC ESTUARY

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

CB-SRBP Technical Paper No. 12
Hetling
FWPCA
Middle Atlantic Region
March 1968

57

SIMULATION OF CHLORIDE CONCENTRATIONS IN THE POTOMAC ESTUARY

BY

Leo J. Hetling*

* Now employed as Director of Research Unit, Environmental Health Services, New York State Department of Health, 84 Holland Avenue, Albany, New York.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	I - 1
II.	THE POTOMAC ESTUARY	II - 1
III.	PRESENT AND FUTURE WATER SUPPLY REQUIREMENTS	III - 1
IV.	THE SEGMENTED ESTUARY MODEL	IV - 1
	The Pumping Problem	IV - 2
V.	EVALUATION OF MODEL PARAMETERS	V - 1
	Segmentation	V - 1
	Segment Volumes	V - 1
	Net River Flow	V - 3
	Boundary Conditions	V - 4
	External Sources of Chlorides	V - 6
	Turbulent Exchange Factor	V - 6
	Proportionality Factor	V - 10
VI.	VERIFICATION RESULTS	VI - 1
VII.	SIMULATION	VII - 1
VIII.	DISCUSSION OF RESULTS	VIII - 1
	Validity of the Model and Parametric Analyses	VIII - 1
	Simulation Results	VIII - 3
IX.	CONCLUSION	IX - 1
X.	BIBLIOGRAPHY	X - 1

LIST OF TABLES

Number		Page
1	Present and Proposed Major Waste Water Discharges to the Upper Potomac Estuary	II - 2
2	Present Sources of Water Supply--Washington Metropolitan Area	III - 2
3	Monthly Distribution of Annual Water Usage	III - 3
4	Projected Water Demand--Washington Metropolitan Area	III - 4
5	Potomac Estuary Chloride Model--Physical Parameters	V - 2
6	Potomac Estuary Chloride Model--Interface Parameter	V - 9
7	Hydrologic Conditions Simulated	VII - 2

LIST OF FIGURES

Number	
1	Study Area Map
2	Washington Metropolitan Area Water Supply Needs
3	The Pumping Problem
4	1930-1965-1966 Potomac River Hydrographs
5	1965 Chlorides at Great Falls
6	Relationship Between Chlorides and River Flow at Great Falls
7	Assumed 1965 Lower Boundary Conditions
8	Assumed 1930 Lower Boundary Conditions
9	Potomac Estuary Chloride Model - 1965 Chlorides at Possum Point
10	Potomac Estuary Chloride Model - 1965 Chlorides at Maryland Point
11	Potomac Estuary Chloride Model - 1965 Chlorides October 8, 1965
12	Potomac Estuary Chloride Model - 1930 Chlorides at Indian Head
13	Potomac Estuary Chloride Model - 1930 River Flows--2010 Water Use--Waste Discharge Out of Basin
14	Potomac Estuary Chloride Model - 1966 River Flows--2010 Water Use
15	Potomac Estuary Chloride Model - 1930 River Flows--2010 Water Use--Parametric Analysis I
16	Potomac Estuary Chloride Model - 1930 River Flows--2010 Water Use--Parametric Analysis II

I. INTRODUCTION

A significant water resource problem in the Potomac River Basin is the provision of an adequate water supply to meet the projected needs of the rapidly growing Washington Metropolitan Area. The conventional approach to this problem would be the construction of upstream reservoirs to supply the required water. However, rapid changes in technology and state of our social-economic outlook are forcing planners to look at an ever-enlarging matrix of solutions to water resource problems.[1] In this case, conflicting interests are exerting significant pressure against the construction of these reservoirs.[2]

Use of the upper Potomac Estuary as a water supply source has been proposed as an alternative to the upstream reservoirs. This proposal has been discarded previously because waste water treatment technology was lacking [It is projected that the rate of waste water being discharged to the upper Estuary will increase from its present rate of 270 million gallons per day (mgd) to over 800 mgd by the year 2010.], and because of uncertainty concerning the possibility of salinity (chloride) intrusion from the Chesapeake Bay if large withdrawals of fresh water from the upper Estuary were made. Advances in the technology of waste water treatment are rapidly eliminating the first objection, except for the buildup of chlorides and total dissolved solids. The purpose of this paper is to present the results of a simulation

Reproduced from best available copy.

model of chloride concentrations in the upper Estuary. It is hoped that these simulation results will prove useful to water resource planners in this critical area.

II. THE POTOMAC ESTUARY

The Potomac River is the second largest river in the Middle Atlantic states. Its tidal section begins in the Washington, D. C., Metropolitan Area at Little Falls and extends 116 miles southeastward to the Chesapeake Bay (Figure 1). The Estuary is several hundred feet in width at the head and broadens to nearly six miles at its mouth. A channel with a minimum depth of 24 feet is maintained in the Estuary up to Washington, D. C. Except for the channel and depths up to 80 feet just below Chain Bridge, the Estuary is relatively shallow.

The Estuary is bounded by the large metropolitan areas of Washington, D. C., and Arlington and Alexandria, Virginia, in its upper part and by forest and farmland in the lower portion.

Several waste water treatment plants presently discharge treated waste to the Estuary, and several more are projected in the future. These are shown in Figure 1. Additional information on these plants is given in Table 1.

TABLE 1

PRESENT AND PROPOSED MAJOR WASTE WATER DISCHARGES TO THE UPPER POTOMAC ESTUARY

Plant Name	Discharge Point (Miles from Chain Bridge)	Present*		1985		2010	
		Population Served x 1000	Flow (mgd)	Population Served x 1000	Flow (mgd)	Population Served x 1000	Flow (mgd)
Arlington County Sewage Treatment Plant	8.9	191	17.3	244	39.0	282	52.2
District of Columbia Water Pollution Control Plant	10.0	1,400	217.1	2,056	328.9	3,085	570.7
Alexandria Sewage Treatment Plant	12.2	138	16.0	220	35.2	291	53.8
Fairfax County Westgate Sewage Treatment Plant	12.3	120	10.2	90	14.4	92	17.0
Washington Suburban Sanitary Commission, Piscataway Creek Sewage Treatment Plant	18.0	**	**	189	30.2	310	57.4
Fairfax County Little Hunting Creek Sewage Treatment Plant	19.6	3.3	2.6	28	5.0	32	5.9
Fairfax County Dogue Creek Sewage Treatment Plant	22.0	3.9	1.4	31	5.0	46	8.5
Fairfax County Accotink Creek Sewage Treatment Plant	24.0	**	**	183	29.3	300	55.5
Charles County Pomonkey-Marbury Sewage Treatment Plant	28.0	**	**	40	6.4	91	16.8

* 1966 Average

** Plant presently not in existence or not of significant size

III. PRESENT AND FUTURE WATER SUPPLY REQUIREMENTS

The present status of the major water supply systems in the Washington Metropolitan Region is given in Table 2. It can be seen from this table that presently 72 per cent of the area's water needs are supplied by the Potomac River.

In estimating future water supply demands, the data presented in Volume 5 of the Corps of Engineers 1962 Potomac River Basin Report[3] was used. The report's conclusion that in the future only 92 mgd would be available from sources other than the Potomac River was also accepted. A more recent report[4] indicates that this is a conservative assumption, and that local sources other than the Potomac will provide a safe yield of 110 mgd in 1985 and 150 mgd in 2010.

Although more recent, possibly more exacting, demand data could be developed, they should not change the major conclusions of the simulations.

Because of the time-dependent nature of the system, it was necessary to estimate the distribution of the annual demands by month. An analysis of the 1960 to 1965 records of the Corps of Engineers Washington Aqueduct Division gave the distribution of filtered water pumped to the District of Columbia shown in ble 3.

Using the above monthly distributions and the base data from the Corps of Engineers report, the water demands on the Potomac River shown in Table 4 were developed. These data,

shown graphically in Figure 2, clearly indicate the need for the development of additional supplies.

TABLE 2

PRESENT SOURCES OF WATER SUPPLY
WASHINGTON METROPOLITAN AREA

Water System	Source	Use (mgd)
District of Columbia	Potomac River	148
Arlington County	Potomac River	20
City of Falls Church - Fairfax County Water Authority	Potomac River	11
Fairfax County Water Authority	Wells	2
Fairfax City	Goose Creek	3
Washington Suburban Sanitary Commission	Patuxent River	47
Washington Suburban Sanitary Commission	Potomac River	43
Rockville City	Potomac River	4
Alexandria Water Company	Occoquan Creek	30
Other Miscellaneous Small Systems	---	9
	Sub-total Potomac River	230
	Sub-total Other Sources	90
	Total All Systems	320

TABLE 3

MONTHLY DISTRIBUTION OF ANNUAL WATER USAGE

Month	Mean Monthly Use*	Mean Monthly Use / Average Annual Use
January	148.5	0.883
February	148.2	0.881
March	148.8	0.885
April	154.1	0.916
May	168.9	1.004
June	189.7	1.128
July	206.1	1.225
August	204.7	1.217
September	183.9	1.093
October	161.9	0.962
November	153.2	0.911
December	150.6	0.895
Average	168.2	1.000

* Mean value of filtered water pumped from 1960 to 1965.

TABLE 4

PROJECTED WATER DEMAND--WASHINGTON METROPOLITAN AREA

Month	1985 Gross Demand (mgd)	1985 Available from Other Sources (mgd)	1985 Net Demand from Potomac River (mgd)	2010 Gross Demand (mgd)	2010 Available from Other Sources (mgd)	2010 Net Demand from Potomac River (mgd)
January	513	92	421	907	92	815
February	512	92	420	905	92	813
March	514	92	422	909	92	817
April	532	92	440	941	92	849
May	583	92	491	1,031	92	939
June	655	92	563	1,158	92	1,066
July	712	92	620	1,258	92	1,166
August	707	92	615	1,250	92	1,158
September	635	92	543	1,123	92	1,031
October	559	92	467	988	92	896
November	529	92	437	936	92	844
December	520	92	428	919	92	827
Average Annual	581	92	489	1,027	92	935

IV. THE SEGMENTED ESTUARY MODEL

The mathematical model employed in the simulation study was a modification of the model developed by Thomann.[5] This model consists of a system of "n" equations, each describing a mass balance of the material being studied for each of the "n" segments of an estuary. For an estuary where good vertical and lateral mixing may be assumed, these segments are selected along the longitudinal axis of the estuary.

The mass balance over each of the segments includes terms describing changes in chloride concentration caused by advection, dispersion, and, in the case of the segment to which sewage was added, a chloride source. A mass balance constructed for the "i"th segment takes the form:

$$V_i \frac{dC_i}{dt} = Q_i [\xi_i C_{i-1} + (1 - \xi_i) C_i]$$

$$- Q_{i+1} [\xi_{i+1} C_i + (1 - \xi_{i+1}) C_{i+1}]$$

$$+ E_i (C_{i-1} - C_i) + E_{i+1} (C_{i+1} - C_i) \qquad (1)$$

$$+ J_i$$

where

V_i = volume of "i"th segment, cubic feet (cf)

C_i = mean chloride concentration in "i"th segment (lb/cf)

Q_i = net waterflow across the upstream boundary of the "i"th segment (cf/day)

ξ_i = a dimensionless proportionality factor used to estimate concentration at upper boundary of the "i"th segment

E_i = turbulent exchange factor for upstream boundary of the "i"th segment (cf/day)

J_i = rate of chloride addition from external source (lb/day)

t = time (days)

Since for this study 28 estuary segments were employed, a like number of expressions similar to Equation 1 were obtained. This system of 28 linear first order, non-homogeneous, ordinary differential equations may be solved simultaneously by numerical methods using a digital computer or by programming the equations on a relatively large analog computer.[6,7,8] In either case, all terms of the equations must be known in order to simulate the chloride concentration of each segment.

The Pumping Problem

In simulating the future use of the upper estuary as a source of water, it was necessary to modify the above basic model in order to account for the transfer of relatively large quantities of water (and its chloride content) from the uppermost section of the estuary through the city's water supply system and back into section six of the estuary as sewage. This transfer is shown schematically in Figure 3.

To handle this transfer theoretically would mean an extension of the above model into the second dimension. However, a simpler approach was sought and found to be adequately accurate. The simpler approach taken consists of the following sequence of operations:

1. Integrate over a period of time, Δ t (normally 1 day), ignoring the transfers, J_1 and J_2.
2. Stop the integrations.
3. Modify the concentration in segments one and six according to the effect of J_1 and J_6.
4. Resume the integration over the next time period of time, Δ t, again ignoring the flow exchanges and continue in this manner.

A detailed description of the modified simulation model and the computer program has been published.[6] Although the computer program has the capability of distributing the pumped flow to different segments, it was assumed that all wastes were discharged into segment 6. It is projected that over 70 per cent of the waste water will be discharged to this segment. It did not appear that the additional precision in the final results justified the additional office and computer time that would have been required to spacially redistribute the effluent.

V. EVALUATION OF MODEL PARAMETERS

Segmentation

The size of the segments selected represents a compromise between accuracy and computational efficiency. In this case the segments were made small (approximately two miles in length) in the upper critical portion of the estuary and relatively large (six miles in length) near the mouth. The final segmentation chosen is shown in Figure 1.

Segment Volumes (V_i)

The segment volumes were determined from the latest (1965) U. S. Coast and Geodetic Survey navigation charts for the Potomac Estuary which give soundings at mean low water. The water volumes determined by planimetering these charts were increased by an appropriate amount to give estimates of mean tide level volumes. No corrections were made for the small deviations of the mean tidal elevations from the long term mean values upon which the volume calculations were based. The segment volumes used are given in Table 5.

TABLE 5

POTOMAC ESTUARY CHLORIDE MODEL - PHYSICAL PARAMETERS

Segment	Length (Miles)	Volume* (Cubic Feet) x 10^7
1	2.69	25
2	2.09	24
3	1.75	33
4	1.31	40
5	1.87	45
6	2.11	52
7	2.57	76
8	2.19	66
9	2.44	79
10	2.06	65
11	2.25	92
12	3.95	252
13	2.94	170
14	2.93	250
15	4.41	330
16	4.26	445
17	4.42	520
18	4.57	535
19	5.36	620
20	5.20	525
21	5.69	650
22	6.00	1,160
23	6.00	1,593
24	6.00	1,957
25	5.40	1,620
26	8.60	2,165
27	6.00	3,055
28	11.00	5,655

* Mean Tide Level

Net River Flow (Q_i)

The term "Q_i" refers to the net flow into the "i"th segment from the adjacent upstream segment, i.e., the net flow across the i-1,i or upstream boundary of the "i"th segment.

In a dye diffusion study of the estuary,[9] it was found upon examination that the inflows to the estuary, except for the gaged Potomac River flow and the District of Columbia waste discharge, were approximately balanced by losses due to evaporation. Therefore, in order to reduce the number of flow input functions, Q_1 was taken as the gaged Potomac River flow reported for the U. S. Geological Survey gaging station (Leiter Gage) at Washington, D. C.; Q_2 through Q_6 were taken as the gaged River flow minus the quantity of water pumped for water supply purposes; and Q_7 through Q_{28} were set equal to Q_6 plus the sum of all the waste water discharges. In the simulation studies, this was assumed to be equal to 90 per cent of the water pumped.

The net tidal flow into and out of each segment was assumed to be zero over a complete tidal cycle. No consideration was given to the small changes in tidal elevation and, therefore, tidal flow which occur on succeeding days during a lunar tidal cycle.

Hydrographs showing the 1930, 1965, and 1966 River flows used are given in Figure 4.

Boundary Conditions (C_0 and C_{n+1})

In order to solve the system of differential equations, the time variation in chloride concentrations at the upper and lower boundary must be known.

At Great Falls approximately ten miles above the upper boundary, there is a National Water Quality Network Station of the Federal Water Pollution Control Administration. Chlorides are measured at this station at weekly intervals. Since there are no known sources of chlorides between the station and the upper boundary of the model, these values were used in the verification studies. The values measured at this station for 1965 are shown in Figure 5. Upper boundary conditions for 1966 were determined in a similar manner.

No measurements of the chloride concentration of the incoming River flow were made in 1930. In order to construct a 1930 upper boundary, a regression of the log River flow on the log chloride concentration using the 1957 to 1965 data collected at Great Falls Water Quality Network Station was run. This regression gave the following equation.

$$\text{Log Cl} = 3.654 - 0.712 \text{ Log Q} \qquad 2$$

A graph showing this equation is shown in Figure 6. Daily chloride values for 1930 were calculated using the 1930 gaged flows and Equation 2.

Obtaining boundary conditions at the lower boundary proved more difficult. There were no regular measurements of chlorides made at the mouth of the Potomac Estuary. A search of all known sources of data produced the following salinity measurements.

1. Daily surface water salinity measurements were taken by the U. S. Coast and Geodetic Survey at Fort McHenry, Baltimore, from 1914 to the present, and at Solomons, Maryland, since 1954.[10]

2. In an atlas of salinity and temperature by Stroup and Lynn,[11] graphical summaries of the distributions of salinity in Chesapeake Bay measured on various cruises from 1952 to 1961 are given. Seasonal averages for the period 1944 to 1961 are also given.

3. In conjunction with some oyster studies, sporadic salinity measurements were taken approximately seven miles up from the mouth of the Potomac,[12] at Bean's Pier in Smith Creek and at Jones Shore approximately four miles above Point Lookout.

4. Salinity measurements were taken at the mouth of the Potomac River by Chesapeake Bay Institute in conjunction with a Potomac River nutrient study.[13]

All of the above measurements taken in 1965 are plotted in Figure 9. Using all of the data shown in Figure 9, the solid line labeled "assumed 1965 boundary conditions" was drawn. Similarly, the 1963 to 1966 boundary conditions were determined.

For 1930 only (the year of the worst drought on record), the measurements for Baltimore Harbor were available. Using these values and judgment obtained from the study of the 1963 to 1966 records, the solid line marked "assumed 1930 boundary conditions" was drawn as shown in Figure 8. The resultant salinities were then converted to chloride concentrations using the classical relationship:

$$S = 0.03 + 1.805\ Cl$$

where

S = Salinity in parts per thousand

Cl = Chloride concentration in parts per thousand

External Sources of Chlorides (J_i)

Since there are no major chloride producing industries either present or planned in the Washington Metropolitan Area, the only external source of chlorides considered in the simulation is that which is added to the waste water by people. Fair and Geyer[14] report that wastes from the human body contain from 5 to 9 grams of chloride a day. In all of the simulation studies made, the higher value of 9 grams per capita per day was used.

Turbulent Exchange Factor (E_i)

The turbulent exchange factor "E" is calculated for each segment boundary from the expression:

$$E_i\ (cf/day) = \frac{K_i\ A_i}{0.5\ (L_i + L_{i-1})} \qquad 3$$

where the "i" subscript refers to the boundary between segments i-1 and i, "K" is the longitudinal dispersion coefficient (analogous to the classical Fickian diffusion coefficient, expressed in areal units per day), "A" is the cross-sectional area of the boundary plane, and "L" is the segment length.

The above expression is based on Fick's first law of diffusion, i.e.,

$$N_i \text{ (lb/sf/day)} = K \frac{dC}{dx} \qquad 4$$

where "N" is the rate of mass transfer of substance per unit area across a boundary where the spatial gradient of the substance is "dC/dx" ("C" is in lbs/cf) and "K" is defined as above.

If the mean concentration in two adjacent segments is assumed to occur at their midpoints, and the gradient between these midpoints is linear, it can be shown by geometry that:

$$\frac{dC}{dx} = \frac{C_{i-1} - C_i}{0.5\,(L_{i-1} + L_i)} \qquad 5$$

Substituting Equation 5 into Equation 4 gives:

$$N_i \text{ (lbs/sf/day)} = \frac{K(C_{i-1} - C_i)}{0.5\,(L_{i-1} + L_i)} \qquad 6$$

Multiplying Equation 6 by the cross-sectional area across which the turbulent exchange takes place yields the mass flow rate "D_i:"

$$D_i \text{ (lbs/day)} = \frac{A_i\, K_i\, (C_{i-1} - C_i)}{0.5\,(L_{i-1} + L_i)} \qquad 7$$

Substituting Equation 3 into Equation 7 yields:

$$D_i = E_i (C_{i-1} - C_i) \qquad 8$$

which is the expression used in Equation 1 to describe the mass flow of substance across a boundary due to turbulent exchange.

The "E" term, or more specifically "K," was the unknown parameter which the verification study was designed to evaluate. The "K" term as used herein is defined as the coefficient of longitudinal dispersion. This term applied to net longitudinal mass transport resulting not only from turbulent diffusion but also from velocity and concentration variations in a cross-section. The latter effect has been shown to be of greater significance in estuary type flows.[15] It has been assumed that dispersion is analogous to Fickian diffusion with the diffusion coefficient replaced by a dispersion coefficient.

The values of "K" for the upper 12 boundaries were obtained from a large-scale dye diffusion study described elsewhere.[9] For the lower 17 boundaries, initial values of "K" were first assumed on an empirical basis.[16] These values were then adjusted to obtain good agreement of the model output with the salinity concentrations observed in the estuary.

A list of the values which gave the best matching between observed and computed values is given in Table 6. These values were used in the simulation studies which follow.

TABLE 6

POTOMAC ESTUARY CHLORIDE MODEL - INTERFACE PARAMETER

Interface	Area (A_i) (Sq. Ft.)	Longitudinal Dispersion Coefficient (K_i) (Sq. Mi/day)	Turbulent Exchange Factor (E_i) (Cu. Ft/day) x 10^8
0-1	4,610	0.00	0.000
1-2	30,000	0.05	0.033
2-3	24,300	0.10	0.067
3-4	29,000	0.15	0.150
4-5	34,300	0.20	0.228
5-6	32,700	0.25	0.217
6-7	47,600	0.35	0.376
7-8	49,900	0.45	0.498
8-9	43,600	0.55	0.546
9-10	59,000	0.65	0.900
10-11	66,500	0.75	1.222
11-12	84,900	0.90	1.301
12-13	111,000	1.20	2.041
13-14	130,000	1.50	3.508
14-15	171,000	1.95	4.797
15-16	117,000	2.80	3.990
16-17	221,000	3.90	10.486
17-18	220,000	5.30	13.696
18-19	243,000	6.00	15.505
19-20	193,000	6.00	11.580
20-21	217,000	6.00	12.625
21-22	245,000	6.00	13.279
22-23	490,000	10.00	43.120
23-24	576,000	10.00	50.688
24-25	509,000	10.00	47.149
25-26	604,000	10.00	45.559
26-27	753,000	10.00	54.463
27-28	1,160,000	10.00	72.056
28-29	1,700,000	10.00	81.600

Proportionality Factor (ξ_i)

The proportionality factor "ξ" is used in the first two terms of Equation 1 that describe the advective movement into and out of a segment. This mass movement across the i-1,i boundary due to advection may be expressed simply as the product of the net advective flow "Q_i" and the concentration at the boundary. However, since only the average concentration of the adjacent segments is considered in the model, the concentration at the boundary must be calculated. It can be shown by geometry that, for the case of a linear gradient between the midpoints of two adjacent segments, the concentration at the boundary is given by the first two terms in brackets in Equation 1 where:

$$\xi_i = \frac{L_i}{L_{i-1} + L_i} \qquad 9$$

Equation 9 gives a satisfactory first approximation for the proportioning factor applicable to the i-1,i boundary. To assure a realistic solution, however, the following relationship must be observed:

$$\xi > 1 - \frac{E}{Q} \qquad 10$$

To simplify computations where "Q" was changed frequently, the inequality given by Equation 10 was treated as an equality. So long as the proportionality factor "ξ" remains within the lower limit defined by Equation 10 and the upper limit of unity, the solutions obtained by the model are relatively insensitive to the value chosen for "ξ."

VI. VERIFICATION RESULTS

Various sources of chloride data were used in the verification of the model. The most significant were the data provided by the D. C. Department of Sanitary Engineering and by the Virginia Electric and Power Company's Possum Point Power Station. The D. C. Department of Sanitary Engineering made bi-weekly sampling runs down the Estuary and also obtained daily values at Woodrow Wilson Bridge (12 miles downstream from Chain Bridge), while the Virginia Electric and Power Company runs daily chloride analyses at Possum Point (approximately 40 miles downstream from Chain Bridge).

As stated previously, knowing values of the river inflow and the boundary conditions, the values of "K" were adjusted to obtain good agreement of the model output with observed chloride concentrations. The final results of these adjustments are shown in Figures 9, 10, and 11 for 1965. Similar results were obtained for 1963 and 1964 using the same "K" values.

In attempting to reproduce the 1930 conditions, only the results of one set of 11 grab samples could be found.[17] These data and the computed 1930 conditions are shown in Figure 12.

VII. SIMULATION

With the values of "K" obtained in the verification studies, it was possible to simulate the effects of future diversions into and out of the Estuary system on chloride concentration. In order to investigate the question posed in the introduction and to examine the sensitivity of the results to the assumption made in formulating the model, the simulations shown in Table 7 were made. The results of these simulations are shown in Figures 13 to 16.

TABLE 7

HYDROLOGIC CONDITIONS SIMULATED

River Flow and Boundary Conditions	Water Supply Use and Waste Water Flows	Waste Discharge Point	Other Imposed Conditions
1930	2010	Out of Estuary	None
1930	2010	To present sites	None
1966	2010	To present sites	None
1930	2010	To present sites	Consumptive water use raised by a factor of 6 for last 15 days in October.
1930	2010	To present sites	Dispersion coefficients in upper eight segments increased by one order of magnitude.
1930	2010	To present sites	Expected chloride loading from people doubled.
1930	2010	To present sites	All of above conditions.

VIII. DISCUSSION OF RESULTS

Validity of the Model and Parametric Analyses

The mathematical model utilized in this study is actually a numerical approximation of the partial differential equation which describes the temporal and spatial relationships of a conservative substance in an estuary. Two problems arise in its use here.

1. The model does not completely explain the integrated mechanisms which control the hydrograph of an estuary.

2. The lower portion of the estuary is highly stratified, and the assumption of vertical homogeneity is not actually valid.

The validity of both of the above statements is strongest near the mouth and weakest in the upper estuary. From an engineering and planning standpoint, it was assumed for this study that since the model matched historical data with reasonable accuracy, it has sufficient integrity to predict future effects as long as the simulated conditions are reasonably similar to the verified conditions.

For example, recent studies indicate that the exchange coefficient is not a fixed physical parameter which depends only on tidal velocity and geometry, but that it is a time-varying parameter which depends on density currents set up by chemical concentration (salinity) gradients. Therefore, it must be realized that if there are drastic changes in salinity within the

system caused by diversions, the results of the model must be interpreted with caution.

The most significant case in the simulation study where this (drastic salinity changes) occurred was the one where the waste effluents were pumped out of the system and the chloride concentration rose rapidly to levels never experienced in the system during the verification studies. In this case since the higher chlorides would probably cause an increase in "K" and, therefore, an increase in the rate at which the chlorides were diffused into the upper segments of the estuary, this effect would not change the obvious conclusions of this result.

Another way in which the simulated condition varied significantly from the verified condition is in the direction of river flow in the upper segments. Such a change might also affect the values of "K."

The effect of an increased turbulent exchange factor which might be caused by the changes in the tidal and flow regimes forced on the system in simulations were investigated by varying the value of "K" in the upper eight segments. The results of this study are shown in Figure 15. From Figure 15 it was concluded that the effect of such changes, should they occur, would not change the study conclusions.

The effect of an error in the assumption of a per capita chloride contribution of 9 gm/day to the system was also checked. This rate of chloride addition was doubled, with the results shown

in Figure 15. This shows that major errors in this estimate would have only a small effect on the results.

The effects of a large consumptive withdrawal for a short period (e.g., as might be caused by a major conflagration) was also investigated, and the water withdrawal rate was increased by 50 per cent for the last 15 days of October. None of this increase was returned to the estuary. This had the effect of increasing consumptive use by a factor of six. The results of this simulator, also shown in Figure 16, indicate that such an action would only increase the chloride concentration from 61 to 64 mg/l.

In order to check the possible cumulative effect of all the above conditions, a final simulation run was made with all of the above conditions imposed. This run, also shown in Figure 16, showed an increase in the maximum chloride concentration by 25 per cent should this occur.

Simulation Results

The simulation results shown in Figure 13 indicate that if the water of the upper estuary is used as a water supply source, and the waste water is transferred out of the upper estuary, salinity intrusion will become a significant problem. In such a case, provision for desalting equipment must be made. However, if the present plans to discharge waste to the upper estuary are carried out, the results shown in Figures 15 and 16 show that

it can be used as a source of water supply without a significant problem of chloride buildup occurring.

Even in the extreme event of the water use rate doubling during a critical period, the chloride concentration of the upper estuary did not approach the Public Health Service Standard for drinking water of 250 mg/l.

IX. CONCLUSIONS

1. The results of computations of the temporal and spatial variation in chlorides in the Potomac Estuary using the segmented estuary model developed by Thomann are in reasonable agreement with observed data.

2. Simulation results using this model indicate that if the Washington Metropolitan Area used the upper Potomac Estuary as an auxiliary source of water, the chlorides in the system would not even begin to approach the Public Health Service limits; and thus, desalting equipment would not be required.

X. BIBLIOGRAPHY

1. Davis, Robert K., "The Range of Choice in Water Resource Management: A Study of the Potomac Estuary," Resources for the Future, Inc., Washington, D. C. (in press).

2. Fox, Irving K., "The Potomac Puzzle--Is There a Reasonable Solution?" Atlantic Naturalist, April-June 1962.

3. U. S. Army Corps of Engineers, "Potomac River Basin Study," Water Supply and Water Quality Control, Vol 5, Prepared by Division of Water Supply and Pollution Control, U. S. Public Health Service, Charlottesville, Virginia, 1962.

4. Hazen, Richard, et al, "Future Water Supply, Metropolitan Washington Region, Report No. 1, Requirements and Sources," Metropolitan Washington Council of Governments, Washington, D. C., 1967.

5. Thomann, Robert V., "Mathematical Model for Dissolved Oxygen," Journal of the Sanitary Engineering Division, American Society of Civil Engineers, Vol. 84, No. SA5, Proceedings Paper 3680, Oct. 1963, pp. 1-30.

6. Jeglic, John M., "Mathematical Simulation of the Estuarine Chloride Distribution," Digital Computer Technology and Programming Analysis Memo No. 1033, General Electric Re-Entry Systems Department, Philadelphia, Pa., Feb. 1967.

7. Hetling, Leo J., and Bunce, Ronald E., "A Digital Computer Program for the Steady-State Segmented Estuary Model," (in press).

8. Jeglic, John M., "Mathematical Simulation of the Estuarine Behavior," Digital Computer Technology and Programming Analysis Memo No. 1032, Rev. A, General Electric Re-Entry Systems Department, Philadelphia, Pa., July 1967.

9. Hetling, Leo J., and O'Connell, R. L., "A Study of Tidal Dispersion in the Potomac River," Water Resources Research, Vol. 2, No. 4, Fourth Quarter 1966, pp. 825-841.

10. U. S. Department of Commerce, "Surface Water Temperature and Salinity, Atlantic Coast, North and South America," Coast and Geodetic Survey Publication 31-1, U. S. Government Printing Office, Washington, D. C., 1965.

11. Stroup, E. D., and Lynn, R. J., "Atlas of Salinity and Temperature Distributions in Chesapeake Bay 1952-1961 and Seasonal Averages 1949-1961," Chesapeake Bay Institute, Graphical Summary Report 2, Johns Hopkins University, Baltimore, Md., Feb. 1963.

12. Dunnington, Elgin, Private Communication, Research Biologist, Chesapeake Biological Laboratory, Natural Resources Institute, University of Maryland.

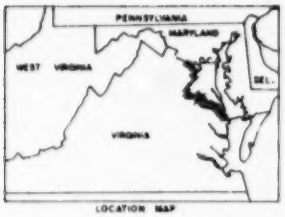
13. Whaley, R. C., Carpenter, J. H., and Baker, R. L., "Data Summary Potomac River Nutrient Cruises 1965-1966," Chesapeake Bay Institute, Special Report 11, Johns Hopkins University, Baltimore, Md., Aug. 1966.

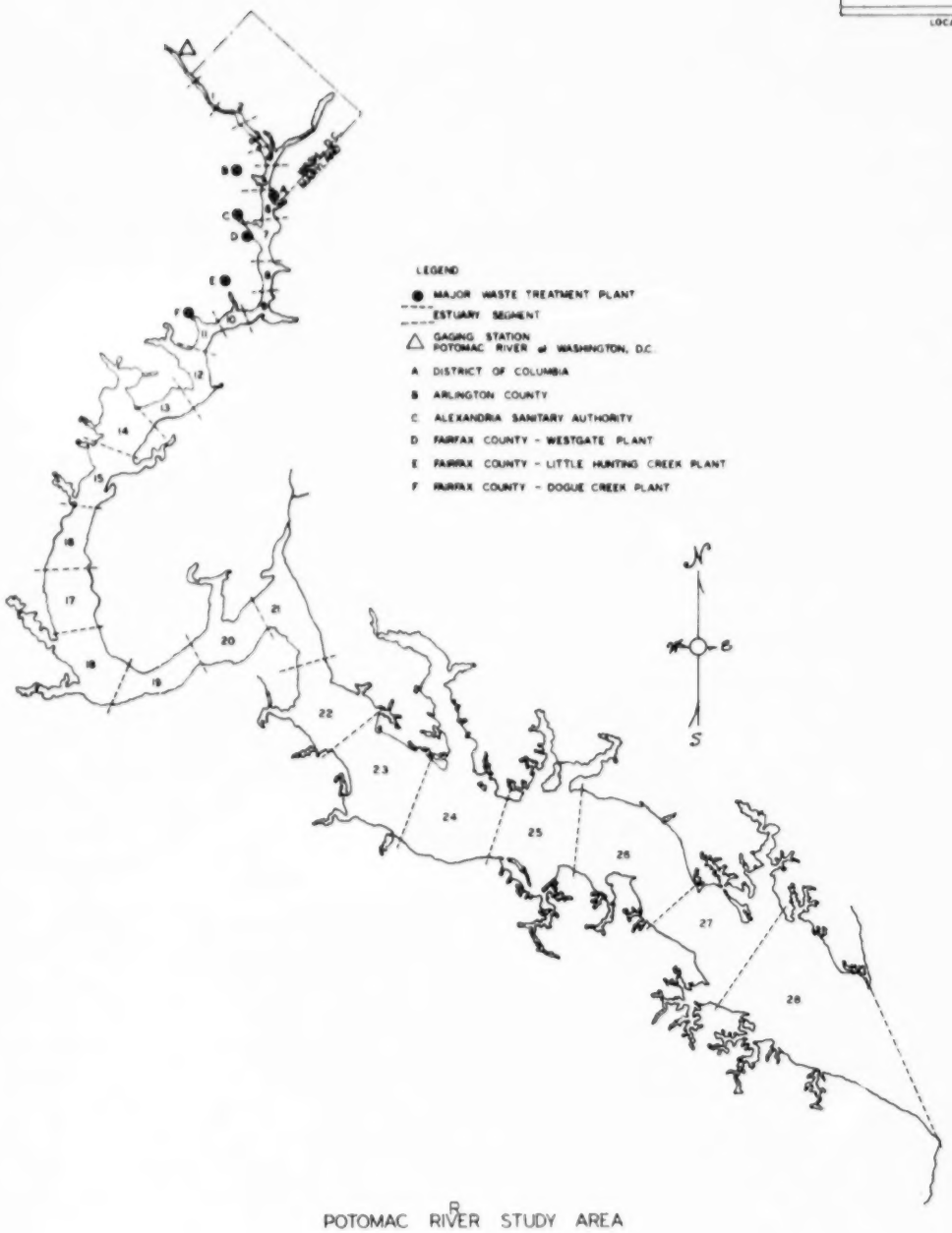
14. Fair, Gordon M., and Geyer, John C., "Water Supply and Waste Water Disposal," John Wiley and Sons, Inc., New York, 1954.

15. Holley, E. R., Jr., and Harleman, D. F., "Dispersion of Estuary-Type Flows," M.I.T. Hydrodynamics Laboratory Report No. 74, Cambridge, Mass., Jan. 1965.

16. Hetling, Leo J., and O'Connell, Richard L., "Estimating Diffusion Characteristics in Tidal Waters," Water and Sewage Works, Vol. 112, No. 10, Oct. 1965.

17. Durford, C. N., "Water Quality and Hydrology in the Fort Belvoir Area, Virginia, 1954-1955," Geological Survey Water Supply Paper 1586-A, U. S. Government Printing Office, Washington, D. C., 1961.





POTOMAC RIVER STUDY AREA

FIGURE 1

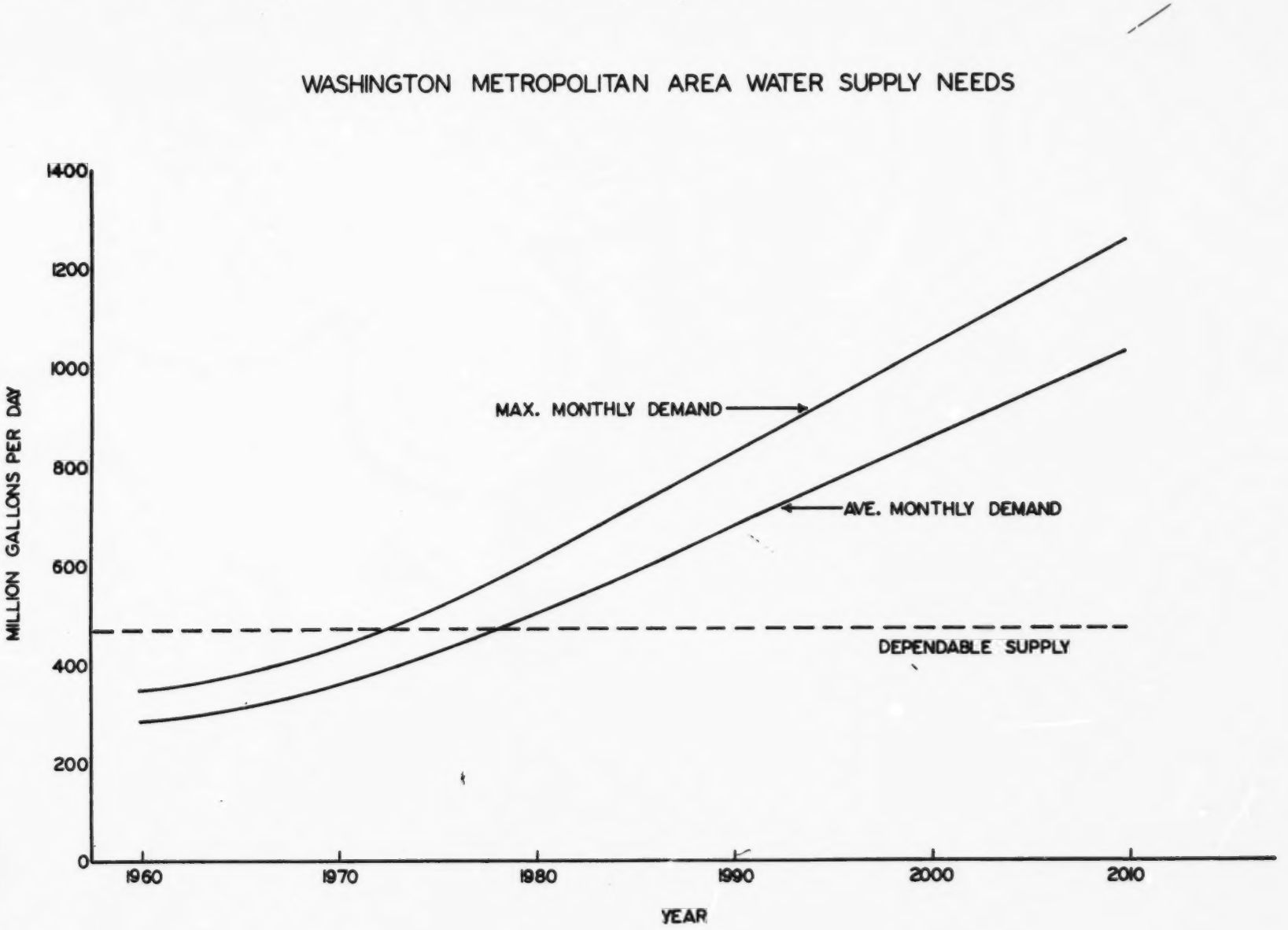

WASHINGTON METROPOLITAN AREA WATER SUPPLY NEEDS
MILLION GALLONS PER DAY
1400
1200
1000
800
600
400
200
0
MAX. MONTHLY DEMAND
AVE. MONTHLY DEMAND
DEPENDABLE SUPPLY
1960
1970
1980
1990
2000
2010
YEAR

FIGURE 2

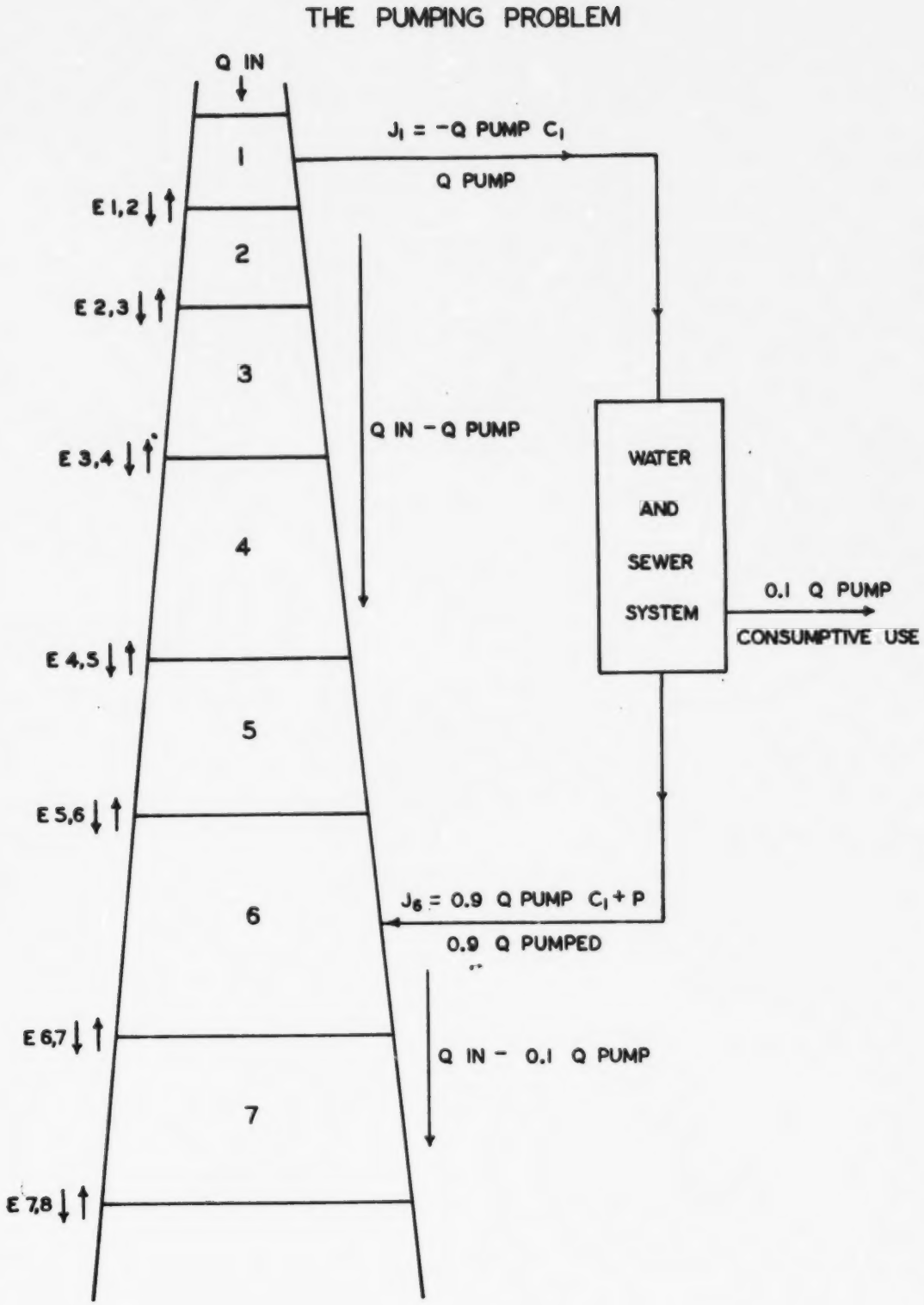

THE PUMPING PROBLEM
Q IN
1
2
3
4
5
6
7
E 1,2
E 2,3
E 3,4
E 4,5
E 5,6
E 6,7
E 7,8
J1 = -Q PUMP C1
Q PUMP
Q IN - Q PUMP
WATER
AND
SEWER
SYSTEM
0.1 Q PUMP
CONSUMPTIVE USE
J6 = 0.9 Q PUMP C1 + P
0.9 Q PUMPED
Q IN - 0.1 Q PUMP

FIGURE 3

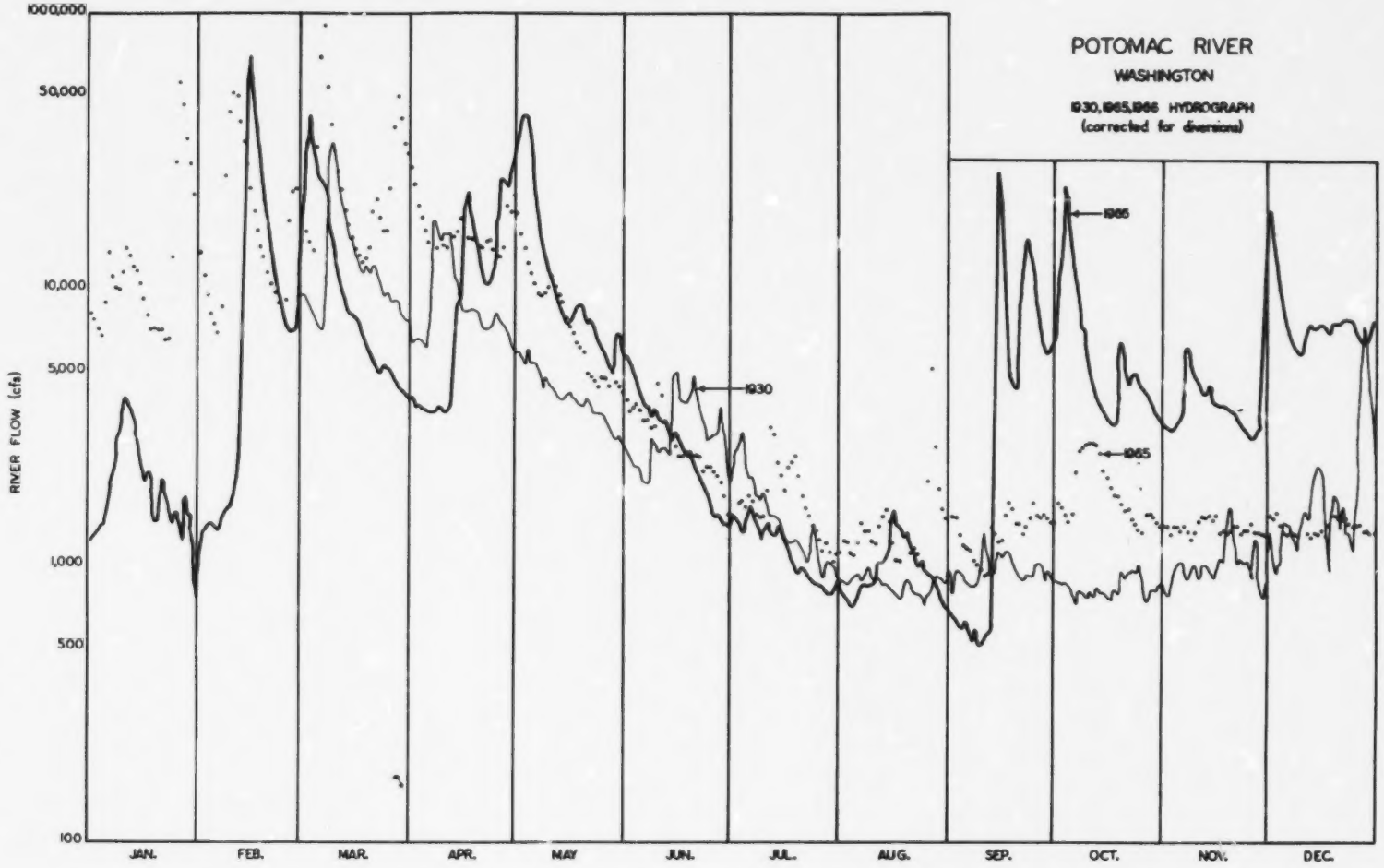

POTOMAC RIVER
WASHINGTON
1930, 1965, 1966 HYDROGRAPH
(corrected for diversions)
1966
1965
1930
RIVER FLOW (cfs)
100,000
50,000
10,000
5,000
1,000
500
100
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 4

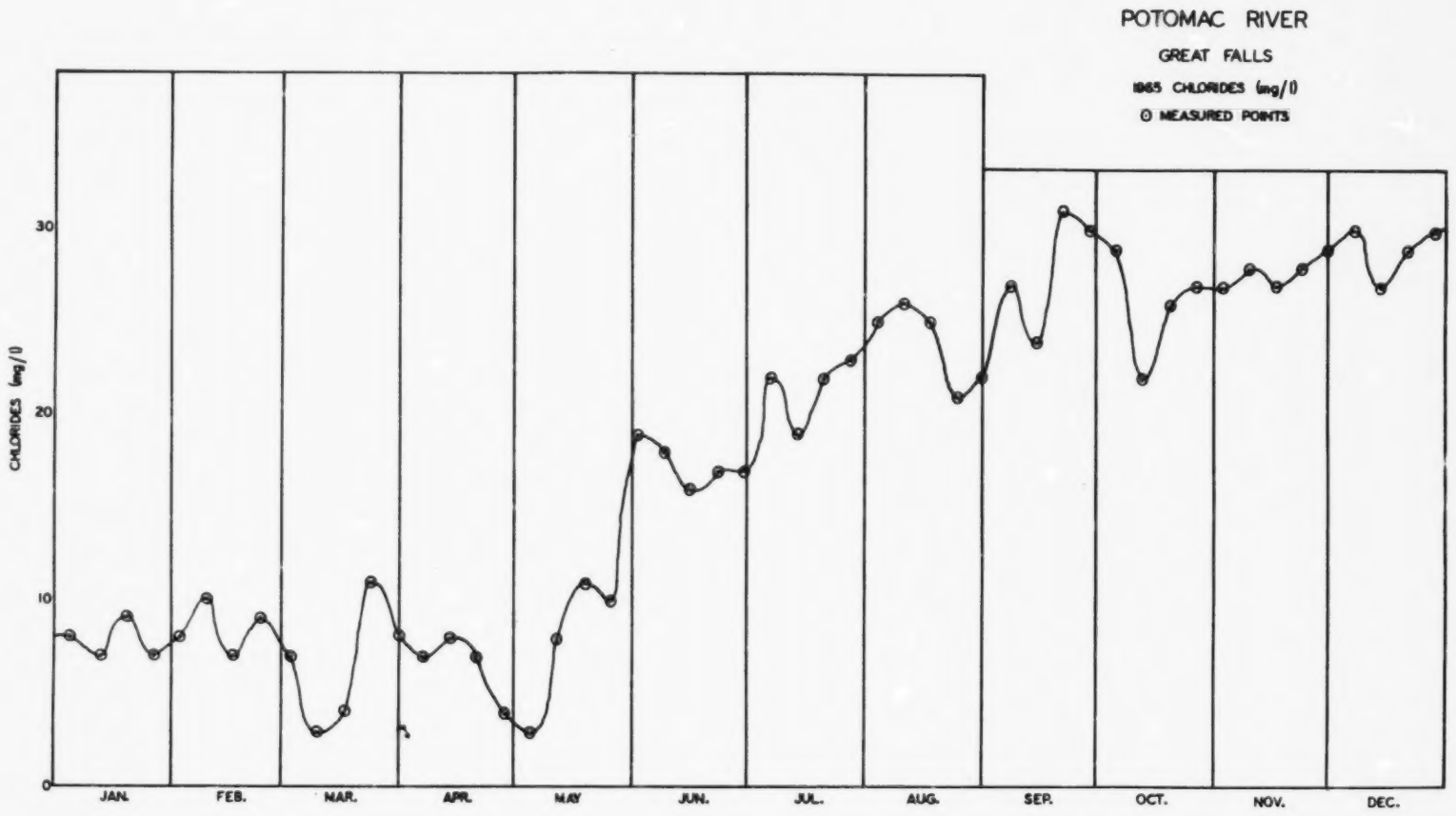

POTOMAC RIVER
GREAT FALLS
1965 CHLORIDES (mg/l)
⊙ MEASURED POINTS
CHLORIDES (mg/l)
0
10
20
30
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 5

POTOMAC ESTUARY

CHLORIDE MODEL
UPPER BOUNDARY CONDITIONS

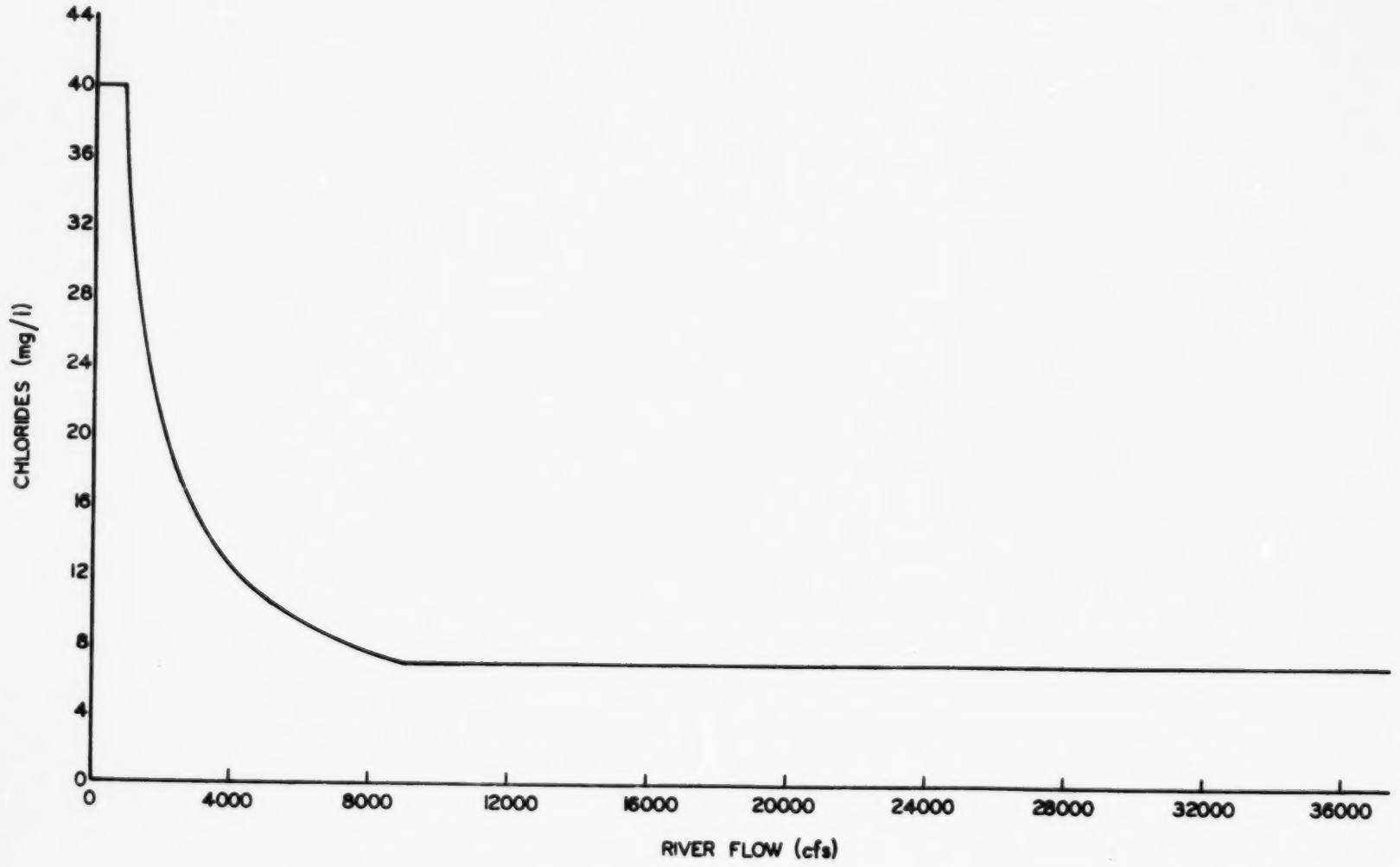


FIGURE 6

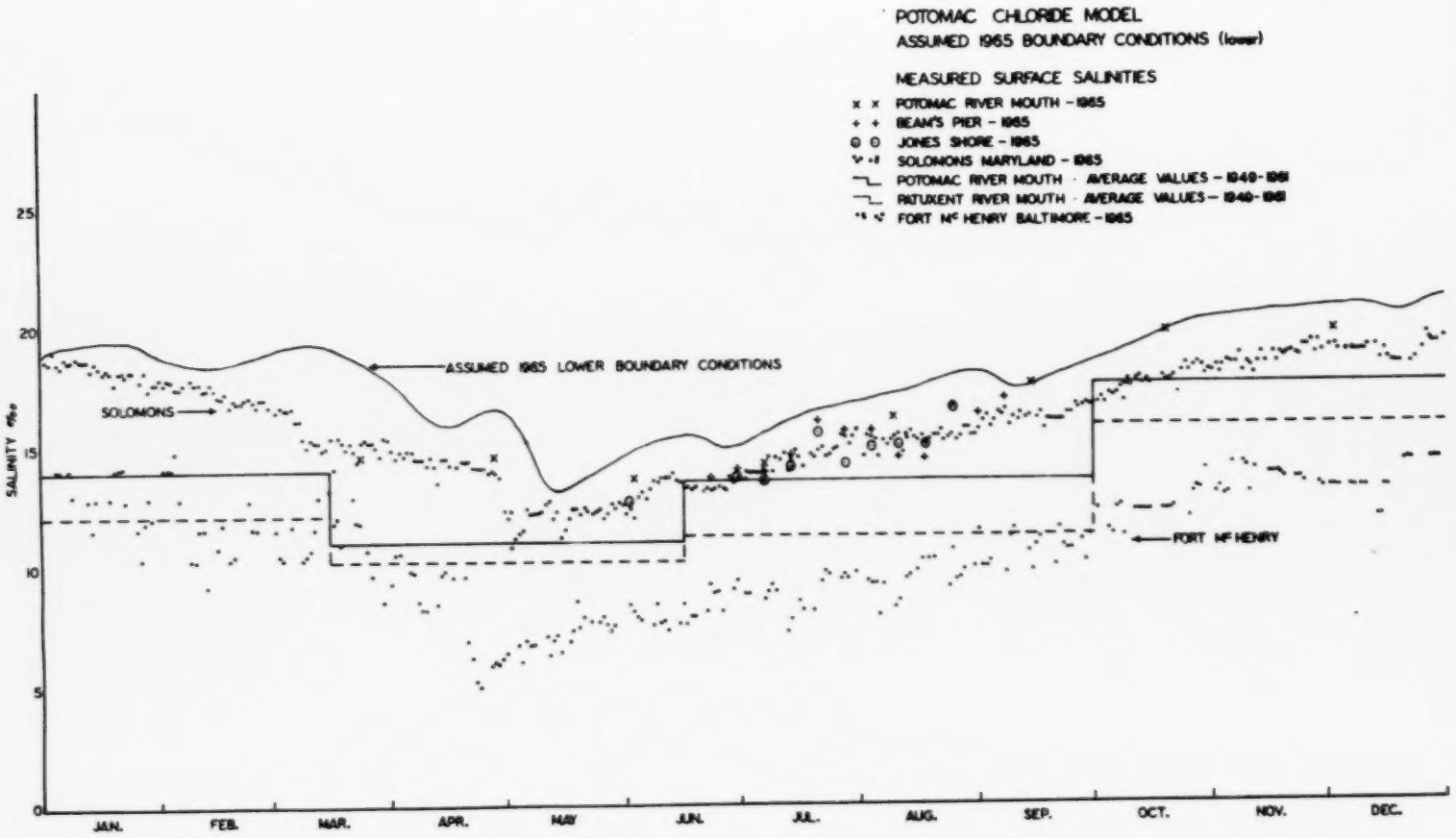

POTOMAC CHLORIDE MODEL
ASSUMED 1965 BOUNDARY CONDITIONS (lower)
MEASURED SURFACE SALINITIES
x x POTOMAC RIVER MOUTH - 1965
+ + BEAN'S PIER - 1965
o o JONES SHORE - 1965
SOLOMONS MARYLAND - 1965
POTOMAC RIVER MOUTH · AVERAGE VALUES - 1940-1961
PATUXENT RIVER MOUTH · AVERAGE VALUES - 1940-1961
FORT Mc HENRY BALTIMORE - 1965
ASSUMED 1965 LOWER BOUNDARY CONDITIONS
SOLOMONS
FORT Mc HENRY
SALINITY ‰
25
20
15
10
5
0
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 7

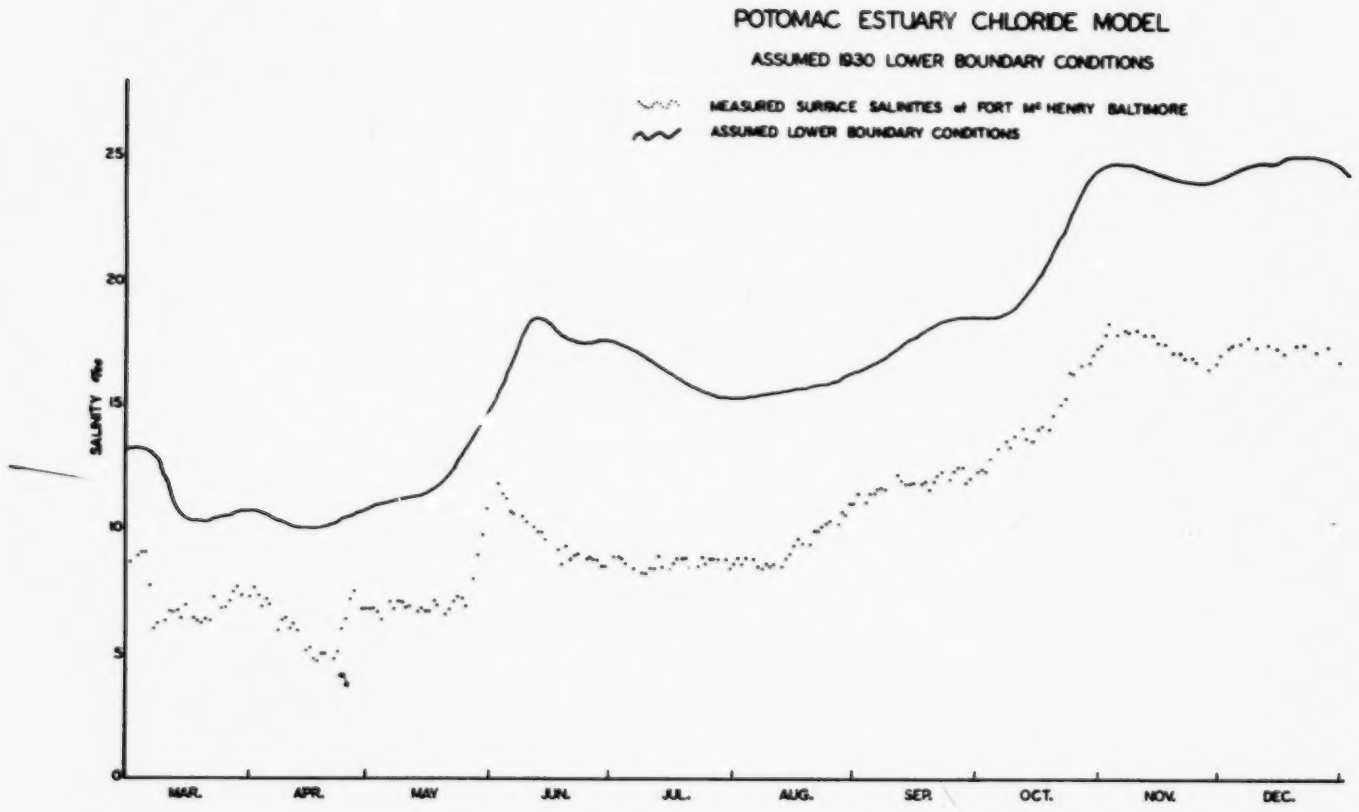

POTOMAC ESTUARY CHLORIDE MODEL
ASSUMED 1930 LOWER BOUNDARY CONDITIONS
MEASURED SURFACE SALINITIES at FORT Mc HENRY BALTIMORE
ASSUMED LOWER BOUNDARY CONDITIONS
SALINITY ‰
0
5
10
15
20
25
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 8

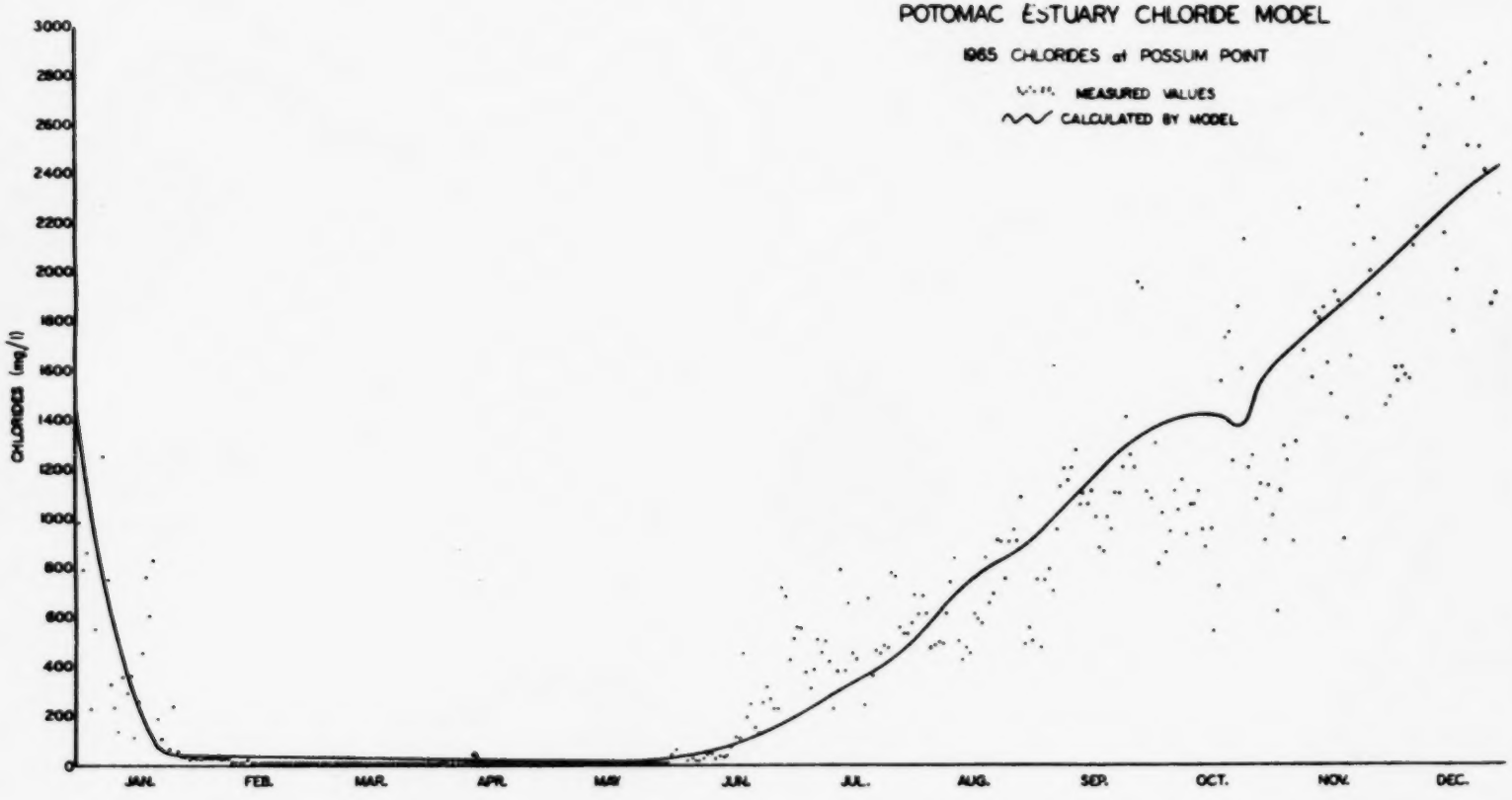

POTOMAC ESTUARY CHLORIDE MODEL
1965 CHLORIDES at POSSUM POINT
MEASURED VALUES
CALCULATED BY MODEL
CHLORIDES (mg/l)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
JAN.
FEB.
MAR.
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 9

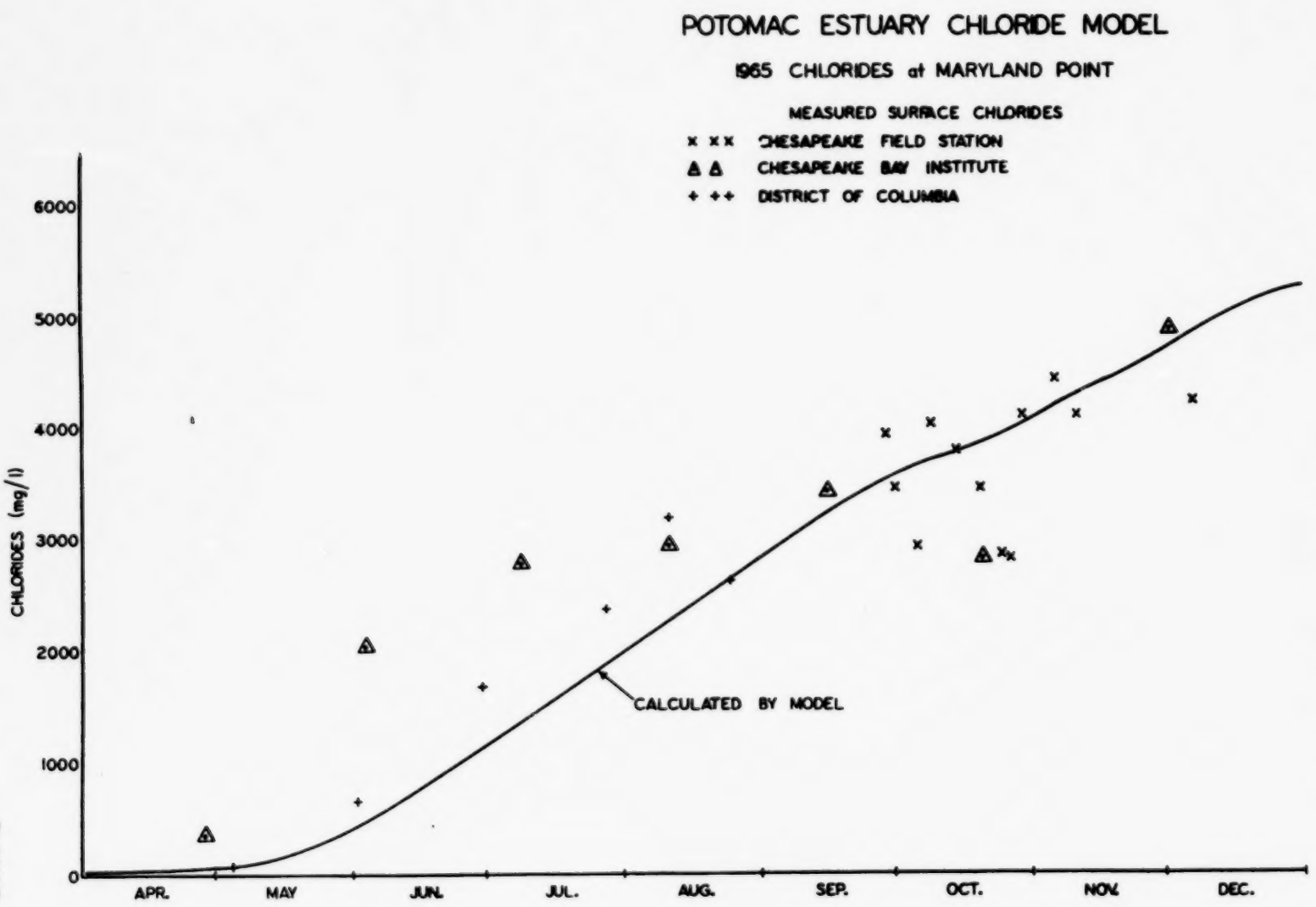

POTOMAC ESTUARY CHLORIDE MODEL
1965 CHLORIDES at MARYLAND POINT
MEASURED SURFACE CHLORIDES
× ×× CHESAPEAKE FIELD STATION
Δ Δ CHESAPEAKE BAY INSTITUTE
+ ++ DISTRICT OF COLUMBIA
CHLORIDES (mg/l)
6000
5000
4000
3000
2000
1000
0
CALCULATED BY MODEL
APR.
MAY
JUN.
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 10

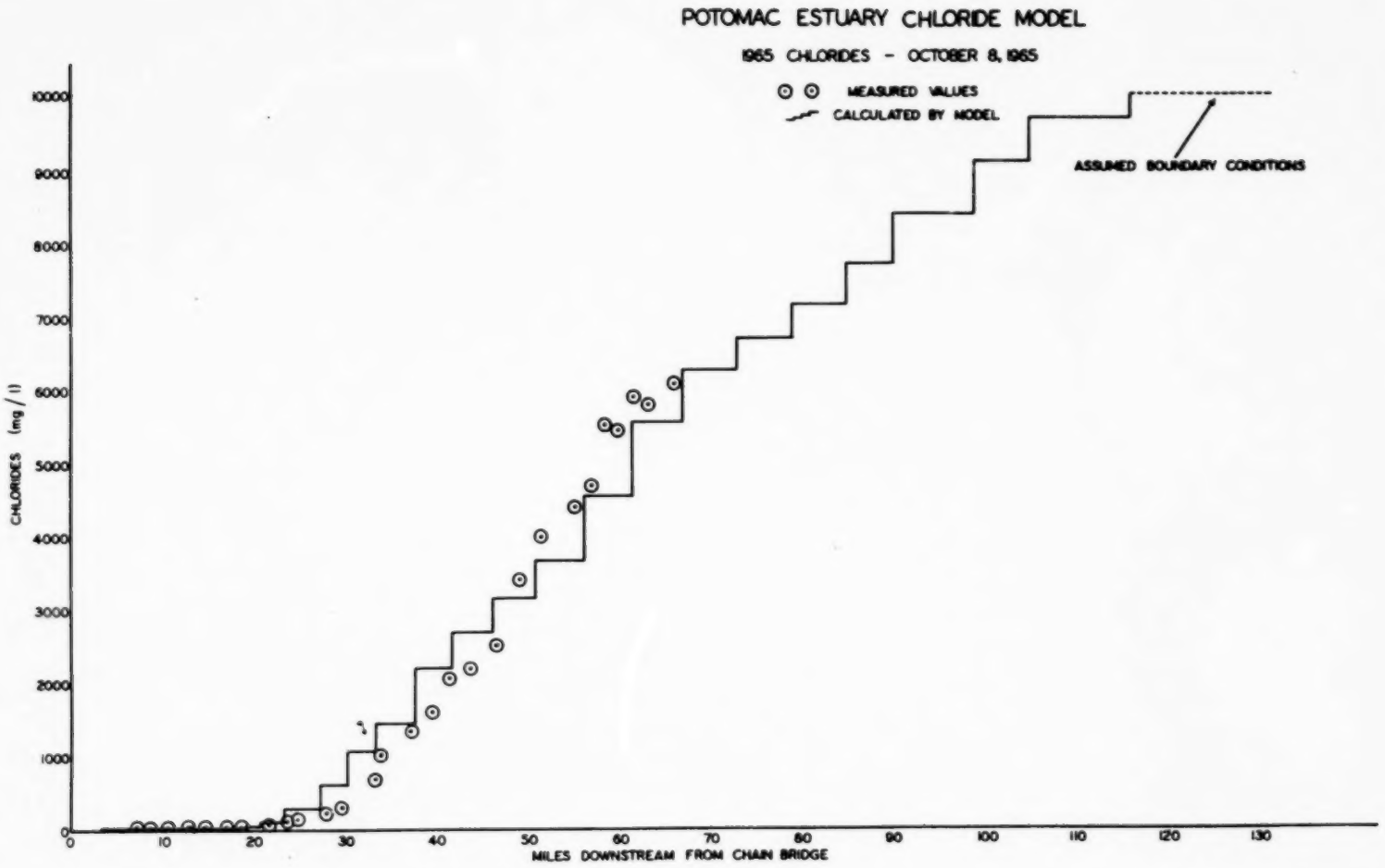

POTOMAC ESTUARY CHLORIDE MODEL
1965 CHLORIDES - OCTOBER 8, 1965
MEASURED VALUES
CALCULATED BY MODEL
ASSUMED BOUNDARY CONDITIONS
CHLORIDES (mg/l)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
10
20
30
40
50
60
70
80
90
100
110
120
130
MILES DOWNSTREAM FROM CHAIN BRIDGE

FIGURE 11

POTOMAC ESTUARY CHLORIDE MODEL

1930 CHLORIDES at INDIAN HEAD

xxx MEASURED VALUES

I I DAILY RANGE OF CHLORIDES FOUND IN ESTUARY OVER A TIDAL CYCLE

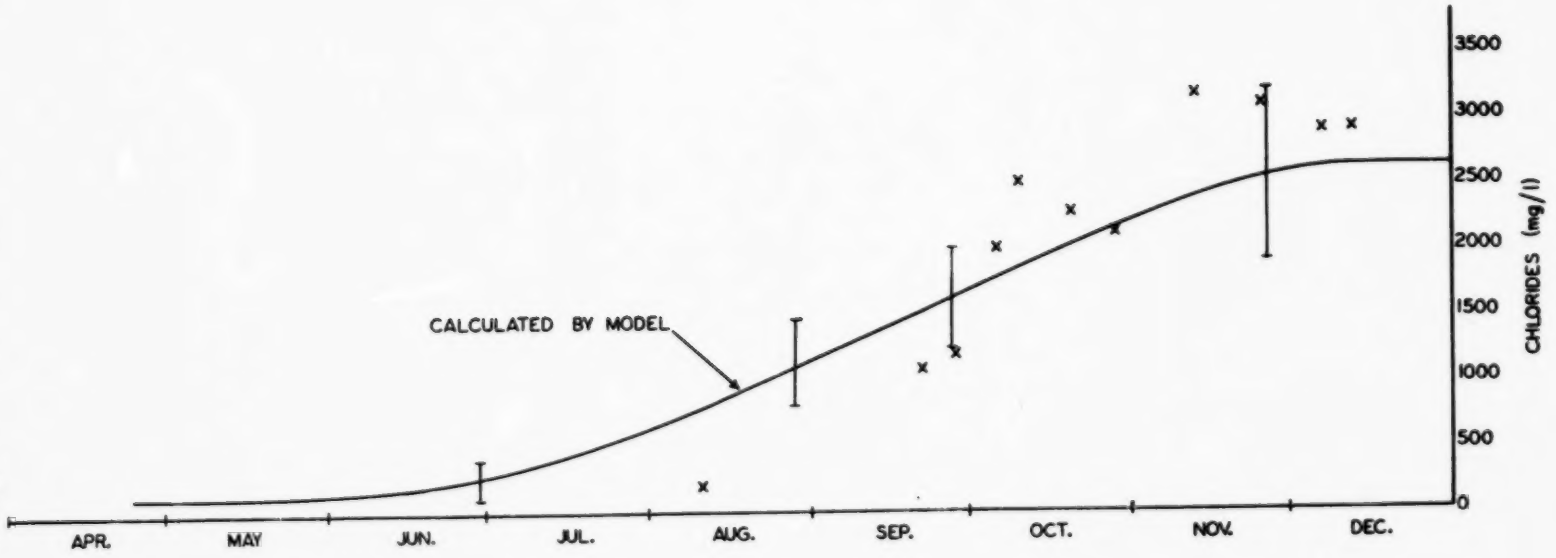


FIGURE 12

POTOMAC ESTUARY CHLORIDE MODEL

CALCULATED CHLORIDE CONCENTRATION at WATER INTAKE BASED ON;

1930 RIVER FLOWS

1930 BOUNDARY CONDITIONS

2010 WATER USE

WATER SUPPLY TAKEN FROM ESTUARY OPPOSITE GEORGETOWN RESERVOIR AND DISCHARGED TO CHESAPEAKE BAY

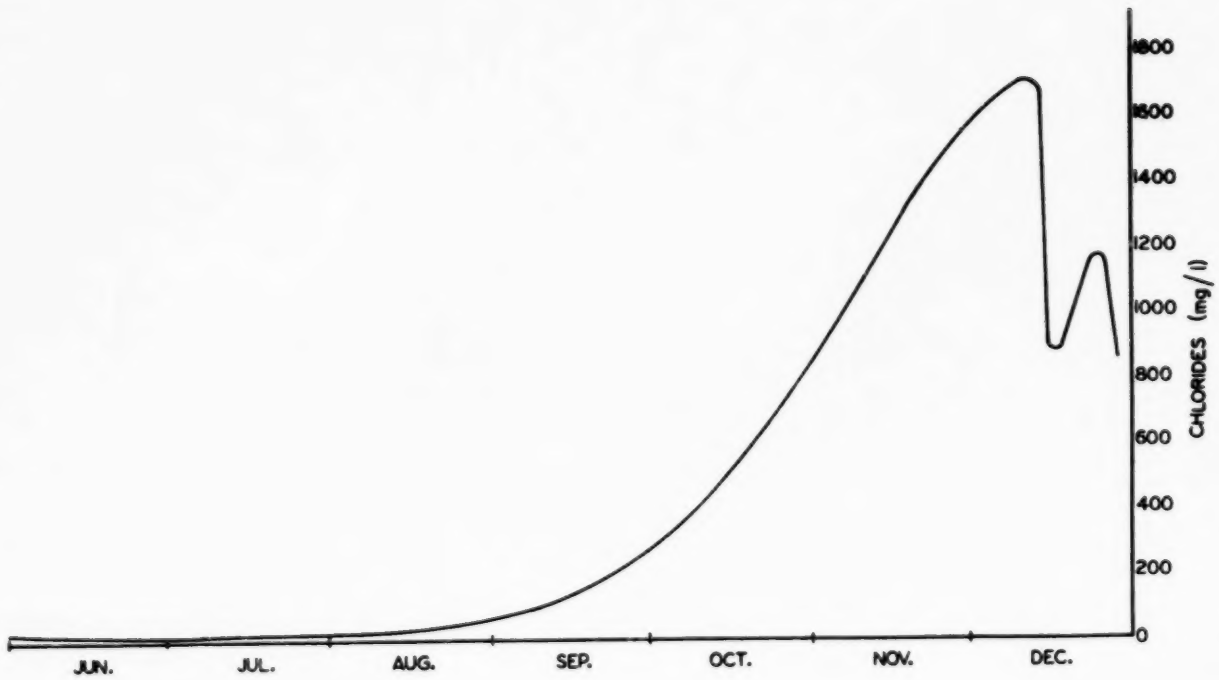


FIGURE 13

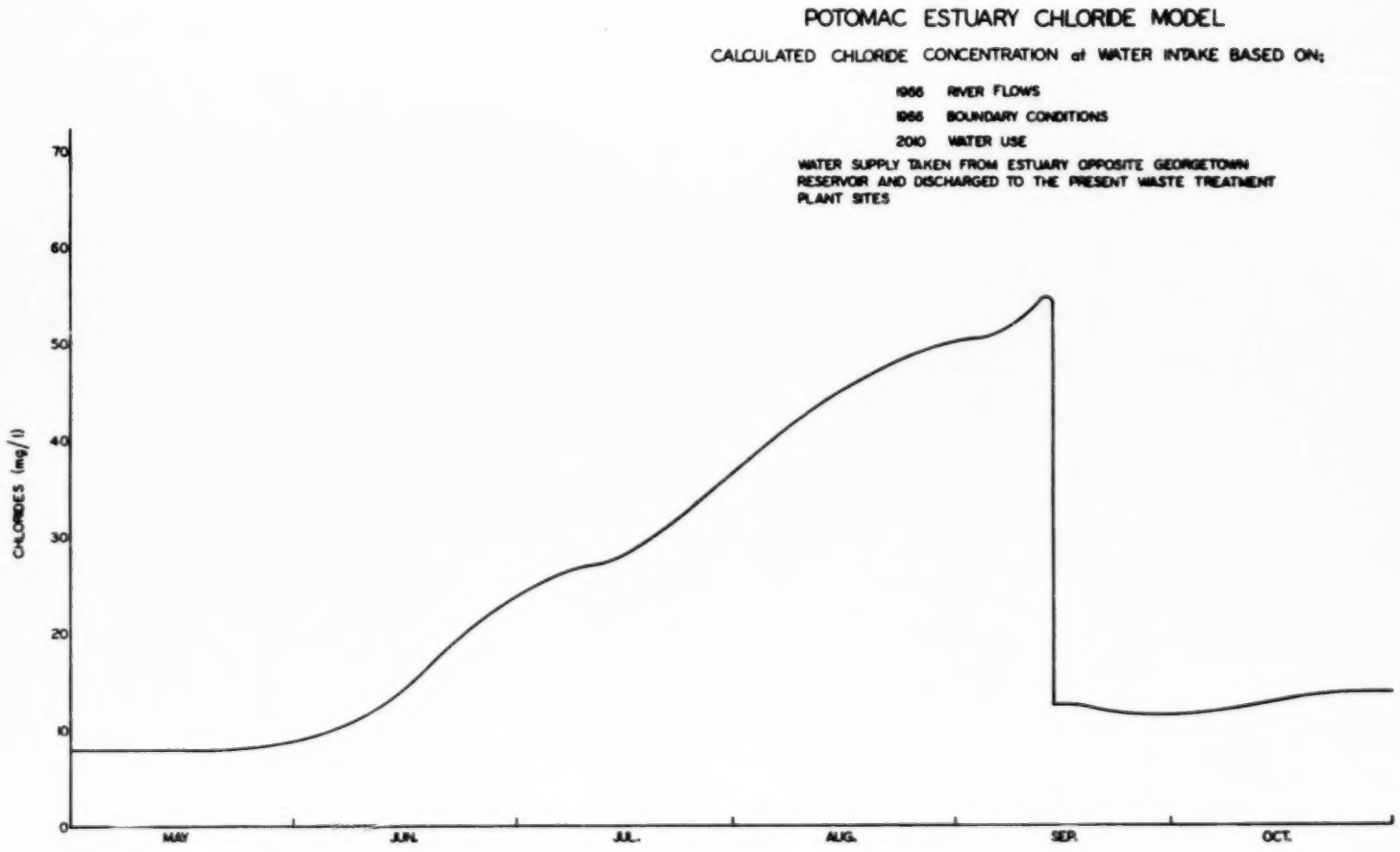

POTOMAC ESTUARY CHLORIDE MODEL
CALCULATED CHLORIDE CONCENTRATION at WATER INTAKE BASED ON;
1966 RIVER FLOWS
1966 BOUNDARY CONDITIONS
2010 WATER USE
WATER SUPPLY TAKEN FROM ESTUARY OPPOSITE GEORGETOWN RESERVOIR AND DISCHARGED TO THE PRESENT WASTE TREATMENT PLANT SITES
CHLORIDES (mg/l)
0
10
20
30
40
50
60
70
MAY
JUN.
JUL.
AUG.
SEP.
OCT.

FIGURE 14

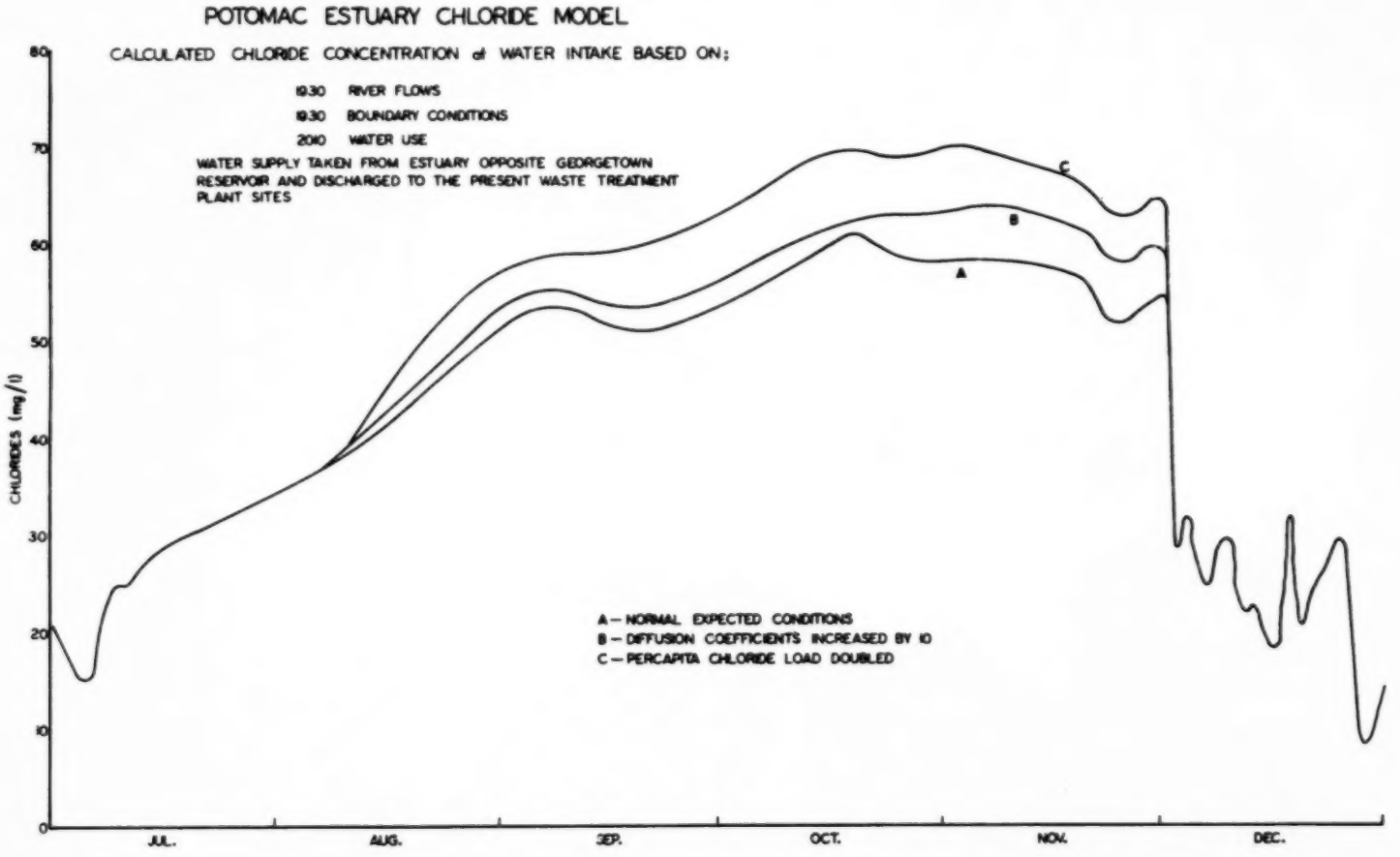

POTOMAC ESTUARY CHLORIDE MODEL
CALCULATED CHLORIDE CONCENTRATION at WATER INTAKE BASED ON;
1930 RIVER FLOWS
1930 BOUNDARY CONDITIONS
2010 WATER USE
WATER SUPPLY TAKEN FROM ESTUARY OPPOSITE GEORGETOWN RESERVOIR AND DISCHARGED TO THE PRESENT WASTE TREATMENT PLANT SITES
CHLORIDES (mg/l)
80
70
60
50
40
30
20
10
0
A
B
C
A – NORMAL EXPECTED CONDITIONS
B – DIFFUSION COEFFICIENTS INCREASED BY 10
C – PERCAPITA CHLORIDE LOAD DOUBLED
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.

FIGURE 15

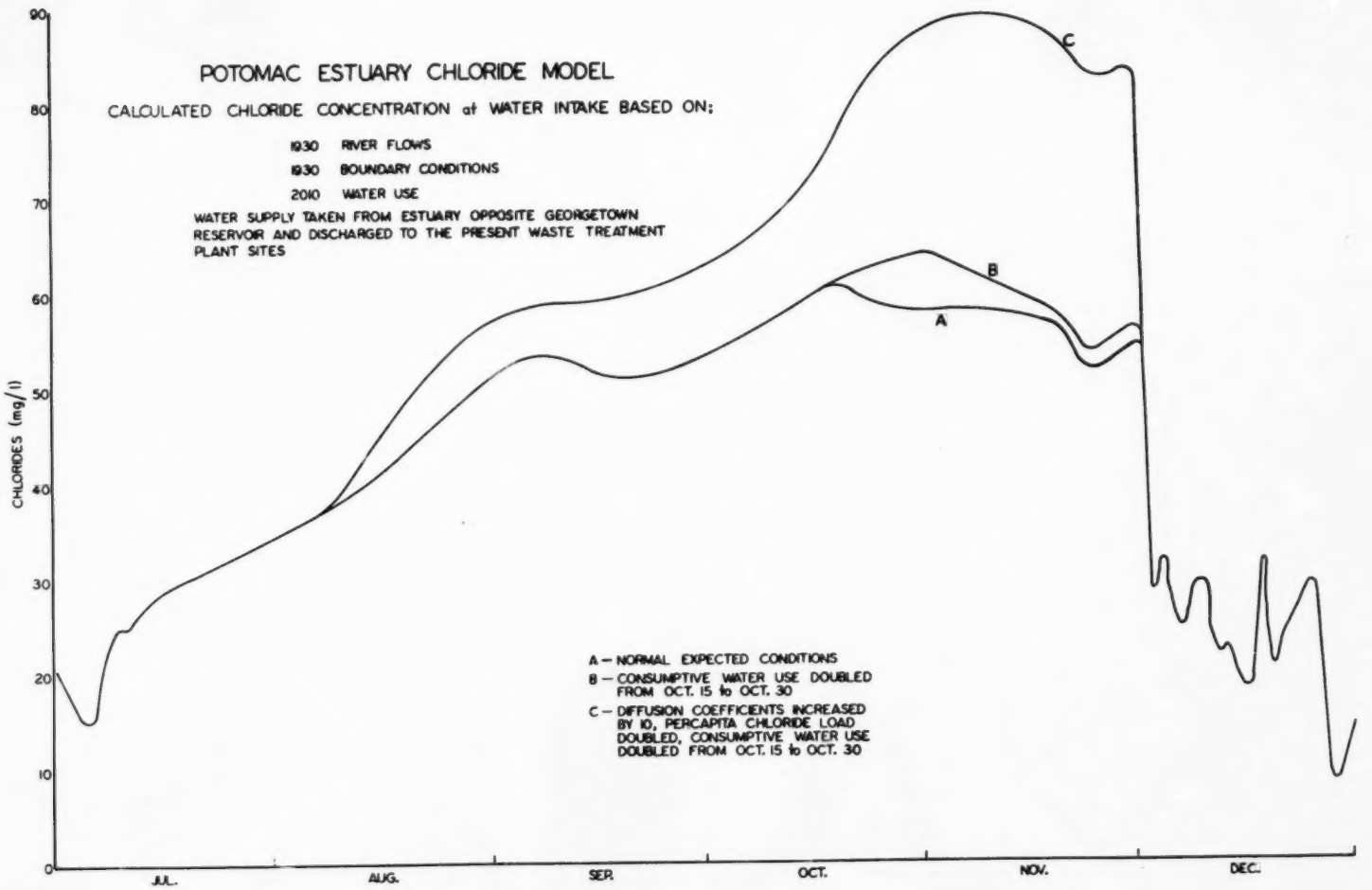

POTOMAC ESTUARY CHLORIDE MODEL
CALCULATED CHLORIDE CONCENTRATION at WATER INTAKE BASED ON:
1930 RIVER FLOWS
1930 BOUNDARY CONDITIONS
2010 WATER USE
WATER SUPPLY TAKEN FROM ESTUARY OPPOSITE GEORGETOWN RESERVOIR AND DISCHARGED TO THE PRESENT WASTE TREATMENT PLANT SITES
CHLORIDES (mg/l)
90
80
70
60
50
40
30
20
10
0
JUL.
AUG.
SEP.
OCT.
NOV.
DEC.
A
B
C
A – NORMAL EXPECTED CONDITIONS
B – CONSUMPTIVE WATER USE DOUBLED FROM OCT. 15 to OCT. 30
C – DIFFUSION COEFFICIENTS INCREASED BY 10, PERCAPITA CHLORIDE LOAD DOUBLED, CONSUMPTIVE WATER USE DOUBLED FROM OCT. 15 to OCT. 30

FIGURE 16